Single Mode Multifiber Expanded Beam Connector for Immersion Cooling System Using GRIN Lens

Alexander William Setiawan Putra
IOWN Business Development Dept.
Hakusan Inc.
Tokorozawa, Japan
a.william@hakusan-mfg.co.jp

Yusuke Ishibashi
IOWN Business Development Dept.
Hakusan Inc.
Tokorozawa, Japan
y.ishibashi@hakusan-mfg.co.jp

Motohito Takezaki
IOWN Business Development Dept.
Hakusan Inc.
Tokorozawa, Japan
takezaki@hakusan-mfg.co.jp

Kazutaka Aboshi
Information & Telecommunication Device Div.
Nippon Sheet Glass Co., LTD.
Sagamihara, Japan
kazutaka.aboshi@nsg.com

***Abstract*— A multifiber single-mode expanded beam optical connector that can provide a stable connection without fiber physical contact has been developed. The connector is less sensitive to the effects of contaminants at the end-face of the connector than an MPO. It can be mated and unmated with ease in an immersive environment.**

Keywords—connector, multifiber, expanded beam, single mode

I. Introduction

One of the methods of cooling for a data center is an immersion cooling system. In this cooling system, the server is immersed in liquid coolant. This method is more efficient than the current air-cooling system and has the potential to decrease power consumption by more than 20% [1]. Current optical connectors, such as an MPO connector, can also be used in this system. However, the connector must be mated before immersion due to the existence of several microns size of unfiltered (the filter size is usually in several tens of microns order) contaminants in the liquid coolant which is risky for mating and un-mating the fiber physical contact-based connectors such as MPO under an immersive environment during maintenance because the contaminant may attach to the end-face of the connector. The performance of the connector may deteriorate. In this case, the whole server rack must be taken out of the liquid coolant before mating and unmating the connector.

In this paper, we report on the development of an expanded beam connector (which is called GrinEB) based on an MPO connection that can provide a high-reliability connection without fiber physical contact. The MPO-based connection is chosen for the first prototype design of GrinEB because MPO is the most standard multifiber connector on the market, which means that special manual or training is not required to handle the connector. It can be readily accepted in the market. Furthermore, GrinEB is more resistant to the contaminants inside the coolant. Hence, in an environment where connector end-face cleaning is difficult, such as an immersion cooling system, it has an advantage.

II. Connector Structure and Design

A. Connector Structure

Fig. 1 shows the male GrinEB and female GrinEB connectors. The male GrinEB connector consists of an MT ferrule with a guide pin, a ceramic ferrule with a GRIN lens, and a metal spacer. The metal spacer creates a gap between the male and female connectors during mating. On the other hand, the female GrinEB consists of an MT ferrule and a ceramic ferrule with a lens. The role of the ceramic ferrules of this connector is as the high-accuracy holders for SELFOC Micro Lens (SML) by Nippon Sheet Glass Company. The SMLs are inserted into the fiber holes of the ceramic ferrule. Then, both sides of the ceramic ferrule are polished and attached to the end face of the MT ferrules using index-matching adhesive. Both the ceramic ferrule and the MT ferrule are flat-polished. Ordinary MPO adapters and MPO housings are used to mate the female and male connectors. Hence, it has the same connection interface as the MPO connector.

B. Beam Expansion and Collimation Design

Fig.2 shows the illustration of the beam diameter expansion and reduction in this connector. The expanded beam is collimated during propagation from the male to the female GrinEB. SML is the type of lens that is based on gradient index optics, where the refraction gradient nature of the lens (GRIN lens) achieves the beam diameter expansion and reduction. The end face of the lens is a flat end. The GRIN lens is chosen for this connector because the characteristics, such as working distance, focal length, and the beam expansion rate of the lens, can easily be modified by modifying the length of the lens itself, unlike the spherical lens, where the curvature of the lens and its radial size have to be adjusted to modify the focal length of the lens. Hence, the SML has more design flexibility than a spherical lens.

Fig.2 also shows the design of the beam expansion in this connector. The design parameters are the mode field diameter (MFD) inside a single-mode fiber (SMF), the expanded beam diameter, the length of the SML, which corresponds to the thickness of the ceramic ferrule, and the distance between the male and female GrinEB. The design was simulated using Zemax. In the current design, the MFD of the beam is

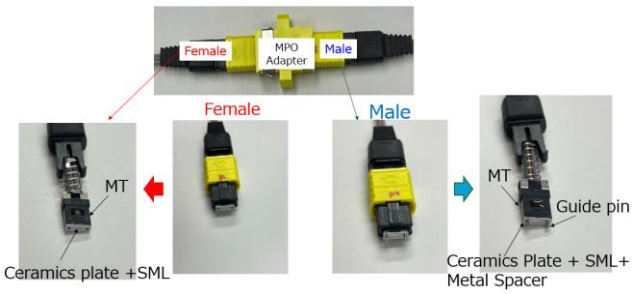

Fig. 1. Structure of GrinEB connector

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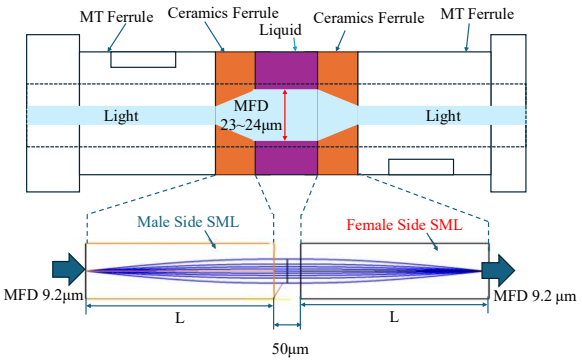

Fig. 2. MFD expansion mechanism of GrinEB connector (not to scale).

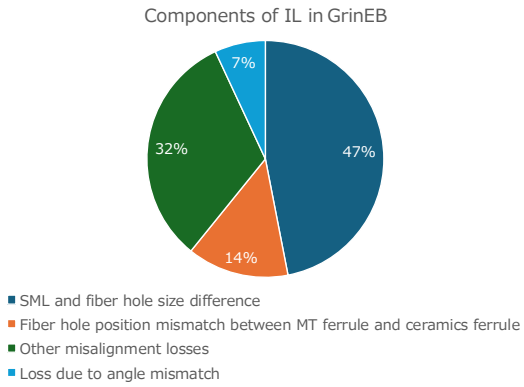

Fig. 3. Components of IL based on simulation.

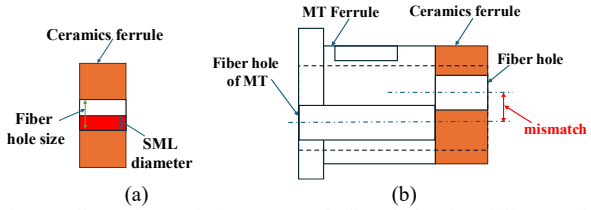

Fig. 4. Illustrations of (a) SML and fiber hole size difference in ceramics ferrule and (b) fiber hole position mismatch.

Fig. 5. Refractive indices profile for theoretical analysis of RL.

expanded from 9.2 μm to around 23-24 μm at the male GrinEB and shrunk back to 9.2 μm at the female GrinEB, and after that, the light is coupled into the SMF. For this design, SMLs with the same length are used at male and female GrinEB to expand and reduce the beam diameter, respectively. Note that, since the SML is inserted into the fiber hole of the ceramic ferrule, the length of the SML is equal to the thickness of the ceramic ferrule.

C. Basic Design Considering the Insertion Loss (IL)

The first target design of insertion loss (IL) for GrinEB is 97% of random mating, with IL to be less than 1.0 dB for an immersive environment. For the analysis, we considered the simulation model of axial and angular misalignment for an ordinary multifiber connector [4]. We combined it with the theory for the lens, using Zemax simulation for analysis. The wavelength of this analysis was 1,310 nm. Fig.3 shows the components that contribute to IL in GrinEB. The simulation shows that the main factors that cause loss are the axial misalignment, which occurs due to the difference in SML diameter and fiber hole size of the ceramics ferrule, and the difference between the fiber hole position of the MT ferrule and the ceramics ferrule. These components are specifically more dominant at the interface between the ceramics ferrule and the MT ferrule at the female GrinEB than the male GrinEB because at this interface, the 9.2 μm beam after beam diameter reduction at SML inside the ceramics ferrule at the female GrinEB is coupled into the SMF. On the other hand, the loss due to angle mismatch in the design of GrinEB was found to contribute less to the IL in the current design of GrinEB. Fig.4 shows the illustrations of these two main contributing factors.

Based on theoretical evaluation in [2] and confirmed by the Zemax simulation, considering the loss at other parts of the connector, to achieve the target design where 97% of IL results of random connection are less than 1 dB, we designed the ceramics holder, which has a fiber hole size of 125.2~125.8 μm and adjusted the SML diameter accordingly. Moreover, we also found that theoretically to achieve IL less than 1 dB and considering other factors of losses, the fiber hole position mismatch between the fiber hole of the ceramics holder and the MT ferrule is around 1.5~1.7 μm [2]. In this case, for this connector, we used a ceramic ferrule with a fiber hole position error ≦ 1 μm and a low-loss MT ferrule with a fiber hole position error ≦ 0.7 μm.

D. Theoretical Analysis of Return Loss (RL)

The analysis of return loss (RL) performance was conducted by first theoretically analyzing the maximum RL that may occur at the GrinEB connector. Fig. 5 shows the refractive indices profile of the theoretical model in this analysis. The refractive indices n1, n2, n, and n3 represent the refractive indices of the fiber (n = 1.45), index matching adhesive, SML, and propagation medium (liquid coolant = 1.44), respectively. The refractive index of SML varies gradually from the center of the optical axis according to:

$$n_r = n_0\left(1 - \frac{Ar^2}{2}\right), \quad (1)$$

Where the n_r, n_0, and A are the refractive index at radius r from the center of the lens, the refractive index at the center of the lens, and a constant, respectively [3].

By assumption of normal incidence of light, power reflectance at each different refractive index interface can be calculated from the Fresnel equation as:

$$R = \left|\frac{n_i - n_o}{n_i + n_o}\right|^2, \quad (2)$$

Where n_i and n_o are the refractive indices of the incident light medium and the other medium at the interface, respectively. From this simple equation, it was calculated that the total RL for GrinEB in an immersive environment without an AR coating was 23.2 dB. Since the performance of RL based on this calculation was lower than the IEC61755-1 grade 4 standard of 26 dB, we applied anti-reflection (AR) coating at

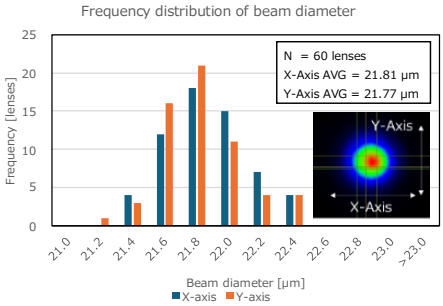

Fig. 6. MFD after expansion by male GrinEB.

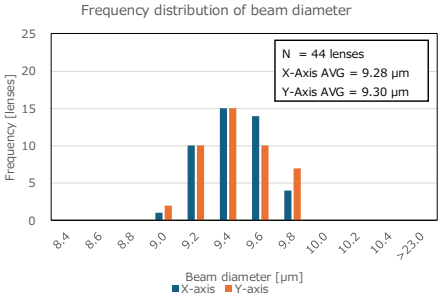

Fig.7. MFD after being shrunk back at female GrinEB.

the end-face of the connector to improve the RL. Theoretically, the RL can be enhanced to more than 26.5 dB with AR coating.

III. Optical Characteristics and Performance

A. Beam Expansion Performance

Fig. 6 shows the MFD after expansion by male GrinEB. The average of the MFD was 21.8 μm, and the maximum of the MFD was 22.4 μm for both the X and Y-axis MFD. A slight difference between the X and Y-axis MFD after expansion shows that the beam was expanded equally in both directions. Hence, the beam shape remained unchanged after MFD expansion. Fig. 7 shows the MFD after the expanded beam was shrunk again at the female GrinEB. This measurement was performed by attaching a ceramic plate with SML into the male GrinEB to verify whether the expanded beam was successfully shrunk back into the MFD of SMF. The average beam size after reduction was 9.3 μm for both the X-axis and Y-axis beam diameters. This condition shows that despite the expanded beam size being slightly smaller than the design of 23~24 μm, the beam was successfully reduced again at the female GrinEB to the size of MFD for SMF. Hence, successful light coupling from the SML to the SMF at female GrinEB can be expected.

B. Insertion Loss

Fig. 8 shows the result of IL evaluation when the connectors were mated in liquid coolant. The optical fiber and the MPO housing were a 12-channel ribbon SMF with an MFD of 9.2 μm at 1,310 nm, and the MPO housing was for the ribbon fiber, respectively. The diameter of guide pins was $\phi 0.6985 \pm 0.0001$ mm. The liquid coolant was liquid type-J, which Eneos Corp manufactured. The wavelength of light in this evaluation was 1,310 nm, and the end-faces of connectors were not AR-coated. The connectors were randomly mated inside the liquid to ensure that the liquid filled the gap between the male and female GrinEB. The average and maximum values of random mating IL for the immersive environment were 0.37 dB and 1.05 dB, respectively. More than 99% of the

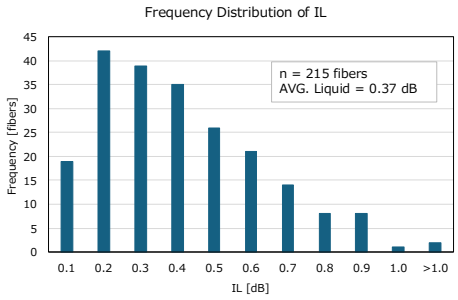

Fig. 8. Frequency distribution of IL for mating in free space and under immersive environment.

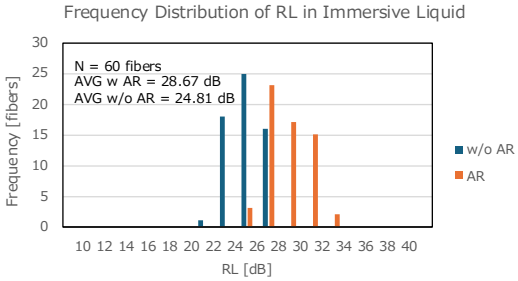

Fig. 9. Frequency distribution of RL for mating under immersive environment.

results were less than 1 dB. Hence, the performance of the connector satisfied the design and the first target of the development.

C. Return Loss Measurement

Fig. 9 shows the frequency distribution of RL measurement results for GrinEB with and without AR coating for measurement under immersive conditions. The measurement was performed at 23.5 degrees Celsius. MPO parts, MT ferrules, liquid coolant, and all other parts were similar to those that were used for IL measurement. The RL measurement was performed using the optical continuous-wave reflectometer (OCWR) method, with a measurement wavelength of 1,310 nm.

The average and maximum RL for measurement under the immersive environment of GrinEB with AR coating were 28.67 dB and 32.67 dB, respectively. On the other hand, the average and maximum RL for measurement in the immersive environment of GrinEB without AR coating were 24.81 dB and 27.90 dB, respectively. These results satisfied the theoretical design of GrinEB with and without AR coating, where the RL was expected to be more than 26.50 dB and 23.20 dB for GrinEB with and without AR coating, respectively. From these results, the improvement of RL with AR coating could be confirmed. Furthermore, the results of GrinEB with AR coating in an immersive environment satisfied the target design of grade 4 for the standard based on IEC61755-1 (RL≧26 dB for flat polished connector).

IV. Performance of Connector under Contaminated Environment

The liquid in the immersion cooling system is filtered regularly to decrease contamination. The size of the filter in the system is around a few tens of microns. In this case, there is no guarantee that contaminants with a particle size of several microns can be completely filtered. In this evaluation, Cerium Oxide with a particle size of 3-5 μm and 99% purity

was used to simulate the contamination inside the liquid coolant. For comparison, we also measured the performance of standard MPO connectors. The exact specifications of MPO housings, guide pins, and optical fibers were used for both MPO and GrinEB, with a wavelength of evaluation at 1,310 nm. The MT ferrule, which was used at the MPO, was an MT ferrule with fiber hole eccentricity ≦ 0.7 μm (97% of IL of less than 0.35 dB for random mating design).

Fig. 10 and Fig. 11 show the 5 times mating IL results of MPO and the GrinEB connector, respectively. Fig. 12 shows the representative results of the fibers' end-face inspection after repeated matings in an immersive environment with contaminated coolant. The contaminated cooling liquid, which was attached to the surface, was cleaned. The contamination concentrations were 1% and 2%, respectively. The number of evaluation cords was one pair, and the connectors were mated 5 times under immersion conditions inside the contaminated liquid coolant without cleaning the end-faces of the connectors before each mating. The evaluation was performed continuously, first at a concentration of 1%, and secondly, at a contamination concentration of 2% without cleaning the end-face of connectors between the evaluations. Moreover, to prevent the sedimentation of contaminants at the bottom of the container, the liquid coolant was stirred before every mating.

Both the MPO and GrinEB connectors experience performance fluctuations due to repeated mating under contaminated immersion conditions. However, some channels of the MPO experienced extreme performance deterioration, and the IL results of certain channels in the MPO deteriorated to more than 4.0 dB, remaining permanently degraded after repeated mating. The end-face of the fiber of MPO from Fig. 12(b) shows that there were several damages at the end-face of the fiber after fiber end-face cleaning, which were the cause of IL deterioration. The cause of permanent damage at the end-face of the fiber at the MPO connector was due to some particles of the contaminants being squeezed at the end-face of the fibers during mating. The MPO connector relies on the physical contacts between fibers, which are pushed by a 10 N spring, to maintain a stable connection. In case of a contaminated environment, some contaminant particles were attached to the end-face of the fibers and squeezed between the fibers during mating. This condition caused damage to the end face of the fibers.

On the other hand, despite the IL fluctuation, the IL of GrinEB remained less than 1.0 dB, with a maximum IL of 0.99 dB, and the end-face of GrinEB did not suffer permanent damage, as shown in Fig. 12(a). Permanent damage at the end-face of the fiber (SML) did not occur at GrinEB because no fiber physical contacts were needed to maintain a stable connection during mating. Furthermore, these results show that GrinEB is more resistant to contaminants at the end-face of the fiber, and GrinEB can be mated and unmated without any problems under a contaminated immersive environment.

V. Summary and Next Step

A GrinEB connector, which provides a stable connection without physical contact with the optical fiber for an immersive environment and is more insensitive to contaminants at the end face of the connector, has been developed. The beam expansion is performed by attaching the ceramic ferrule with SELFOC Micro Lens (SML) at the

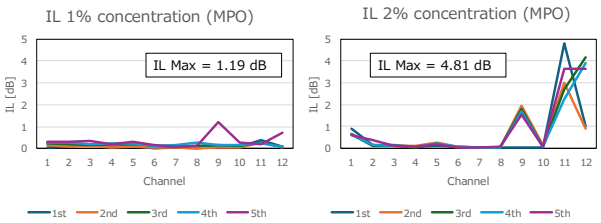

Fig. 10. IL of MPO for 1% and 2% contamination concentration.

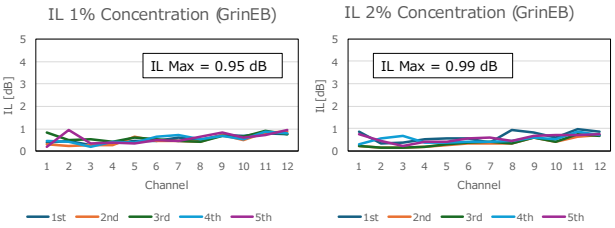

Fig. 11. IL of GrinEB for 1% and 2% contamination concentration.

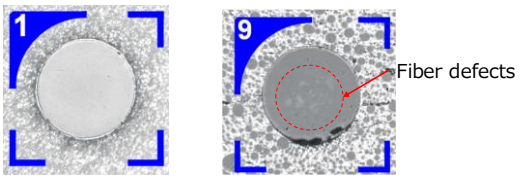

Fig. 12. Representative of fibers' end-face inspection after repeated mating for (a) GrinEB and (b) MPO connector.

end-face of an ordinary MT ferrule. The mode field diameter (MFD) is expanded from 9.2 μm to 21.8 μm at the male GrinEB and shrunk back to 9.2 μm at the female GrinEB to be coupled back to a single-mode fiber. The connection interface is similar to a standard MPO connector. At the end face of the male GrinEB, a metal spacer is attached to create a gap between the male and female GrinEB. Hence, fiber physical contact does not occur during mating.

Insertion Loss (IL) less than 1 dB for more than 97% of random mating results has also been achieved as the first target of development for this connector under an immersive cooling environment. The return loss (RL) of AR coating GrinEB also satisfied the grade 4 standard based on IEC61755-1, with an average RL of 28.67 dB for an immersive environment. Moreover, unlike the MPO connector, GrinEB can also be mated and unmated under a contaminated immersive cooling system without any permanent damage after mating. Hence, it has an advantage in terms of ease of maintenance in immersive conditions over the MPO connector. As the next step, we plan to improve the RL performance of this connector by designing the angled GrinEB, which has an RL of more than 40 dB. Furthermore, we are also exploring other variants with beam sizes of 40 μm and 70 μm, and evaluating their performance.

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